ENERGY AND ECONOMIC EVALUATON OF A HYBRID CAES/WIND POWER PLANT WITH NEURAL NETWORK-BASED WIND SPEED FORECASTING

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ABSTRACT

A model of a hybrid power plant consisting of Compressed Air Exergy Storage (CAES) coupled with a wind farm is presented. The model employs neural network-based wind speed forecasting . By coupling CAES with a wind farm, some of the major limitations of wind power, such as a low power density and an unpredictable nature, can be overcome. The use of time-series neural network-based prediction models aims at reducing the stochastic uncertainty of wind power. As shown in the paper, knowledge of the future incoming energy can be a powerful means for planning the daily operation strategy of the storage system. A detailed economic analysis has been carried out, evaluating investment, maintenance and operational costs using actual energy market prices. The benefits critically depend on the performance of each sub-system, incoming energy, user load and economic regulations. Results show that advantages in terms of Net Present Value, energy savings and CO_2 mitigation can be achieved.

Keywords**:** Exergy, storage systems, CAES, wind power, neural network, wind speed forecasting.

NOMENCLATURE

Latin Letters

E	Electric energy [kJ]
EMI	Energy Management Index: (1 if the CAES is generating, 0 otherwise)
H_i	Fuel heating value [kJ/kg]
k	Prediction time horizon [hours]
m	Mass [kg]
NPV	Net Present Value [M€]
P	Power [kW]
PI	Profitability Index [/]
SPB	Simple pay-back [years]
v	Wind speed [m/s]

Greek letters

η	Efficiency

Subscripts

C	Compressor
f	Fuel
gen	Generated
in	Inlet
out	Outlet
sto	Stored
WT	Wind turbine

1. INTRODUCTION

Some of the major limitations of wind-generated power are represented by its low power density and intermittent nature, largely depending on local site and unpredictable weather conditions [1]. These problems conspire to increase the unit cost of wind generated power, thus limiting deployment [2].

Storage devices with the ability to store large amounts of exergy for several hours, can help in overcoming these problems and others related to wind-generated power.

The storage system considered in this paper is Compressed Air Exergy Storage (CAES). In CAES, exergy is stored in the form of compressed air in a reservoir, usually an underground cavern (salt dome, aquifer and rock caverns) [3][4][5]. Air is compressed and stored during off-peak periods and then used on demand during peak periods to generate power with a turbo-generator system.

The presence of two or more energy sources makes it necessary to adopt suitable strategies to manage the exergy storage system in presence of an unknown future energy demand. This complex scenario makes the analysis of these plants a very difficult task. Therefore, time series neural network based forecasting models have been introduced in order to determine the optimal daily operation and scheduling, as a function of plant location and power demand.

Based on previous works by the authors [6][7][8], the present paper focuses on the model of a hybrid power plant (HPP) consisting of a CAES and a wind farm coupled with wind speed prediction models.

Starting from CAES technical data of the Alabama Electric Cooperative McIntosh Power Plant and wind turbine data provided by GE, a detailed economic analysis has been carried out: investment and maintenance costs are estimated based on literature data, while operational costs due to the electrical energy and the methane are calculated according the actual Italian energy market prices. With respect to the previous papers published by the authors, the economic model has been updated with the latest energy prices (January 2006) and a forecasting model for wind speed has been implemented.

The model of this study has been implemented on a PC Pentium 4, 3.0 GHz, with 512 MB RAM. The computational time to simulate 365 days is about 150 seconds for the simulation of HPP, while it is about 1 second in the case of a wind farm/grid solution.

2. CAES MANAGEMENT

CAES operation can be at any desired power level from 10 MW to 110 MW. The compressors and turbo expanders are sized such that one hour of operation at 100 MW requires about 1.6 hours of compression to maintain the mass balance in the air-storage cavern [5].

Typically during the week the plant operating cycle may involve one or two daily power generation periods of up to 10 hours/day with overnight compression cycles of 10 hours/day. On weekends, the plant is operated in compression up to 30 additional hours to restore the cavern to full pressure.

The cavern is sized to provide a maximum of 2600 MWh of uninterrupted power generation [5].

The proposed CAES plant requires approximately 0.75 kWh of off-peak electrical energy (for storage charging) and 1.37 kWh of thermal energy per kWh of peak energy produced (design operations).

For off-design power production, a decrease in component efficiency produces an increase in the required off-peak electric and thermal energy. Thus, the relationship between produced energy and unit price is neither linear nor trivial. According to the Italian energy market, the unit cost of produced energy is about 8-10 €c/kWh.

2.1 Using wind speed forecasting for CAES/Wind management

Without predicting the incoming wind energy, the net load, above that provided by wind turbines, would be known only in real time. Thus, the only way to manage CAES storage/generation would be to follow the net load for a pre-fixed number of hours; the duration of CAES generation would be function of the load, of the wind power generation and the energy prices.

Because wind speed is variable and not predictable, plant management can be a problem. Mainly, user demand might not be satisfied during some periods. So, forecasting the wind contribution could be very helpful for proper system management.

Knowing the incoming wind power several hours in advance helps in estimating the net load for the current day and thus determining the management strategy. For each day, before the HPP simulation is performed, the following procedure, based on Eqs. 1-4, is used to provide an effective approach to system management.

$$E_{sto}(\text{per week}) = \int_{off-peak\ hours} P_{sto}(t)dt \qquad (1)$$

$$E_{gen}(\text{per day}) = \frac{1}{5}\eta_{gen} \cdot E_{sto}(\text{per week}) \qquad (2)$$

$$E_{gen}(\text{per day}) = \int_{\text{peak hours}} P_{gen}(t) \cdot EMI(t)dt \qquad (3)$$

$$Savings = \mathrm{f}\left(P_{gen}(t), P_{sto}(t), EMI(t)\right) \qquad (4)$$

As a function of the compressor mechanical consumption and of the peak-hours a day, Eq. 1 estimates the stored energy per week. Equation 2 gives an estimate of the energy that can be generated per day, uniformly distributing the stored energy over the week and taking into account the generation efficiency (estimated through previous simulations). *EMI(t)* is introduced in Eq. 3 to estimate the daily generated energy. In this equation, P_{gen} represents the net electric load (above that provided by wind turbines) estimated by the wind speed forecasting. *EMI(t)* affects the daily savings of the hybrid power plant and its values are found by maximizing Eq. 4.

2.2 Artificial Neural Networks approach

As discussed in [9][10], the forecasting of wind power is beneficial for the optimum operation of a power system with a significant contribution from wind. Wind forecasting is currently done by adopting complex atmospheric models or by using statistical time-series analysis.

Therefore, an artificial neural network model (Fig. 1) can be very helpful because it is able to perform a time series forecast.

Refer to [11] for a detailed discussion.

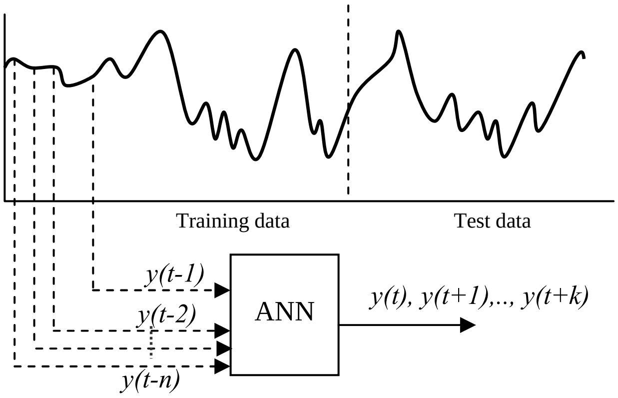

Fig. 1: Artificial neural network logical scheme

The forecasting model has been tested for different prediction time horizons *k*; some results are shown in Table 1 and a test set with *k=14* (value assumed in this study) is shown in Fig. 2 and Fig. 3.

Table 1: ANN performance as function of forecasting time horizon

Time horizon, k [hours]	*Average error on test data [m/s]*	*RMS error [m/s]*	*Error on the whole year data set [%]*	*Error on 300 hours data set [%]*
3	0.6921	0.9310	20.1863	12.4269
6	0.8725	1.1544	25.4490	14.7211
14	1.1035	1.4734	32.1874	21.2640

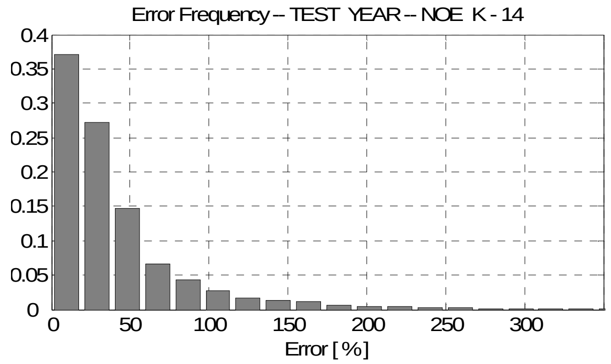

Fig. 2: Error frequency (time horizon – 14 hours)

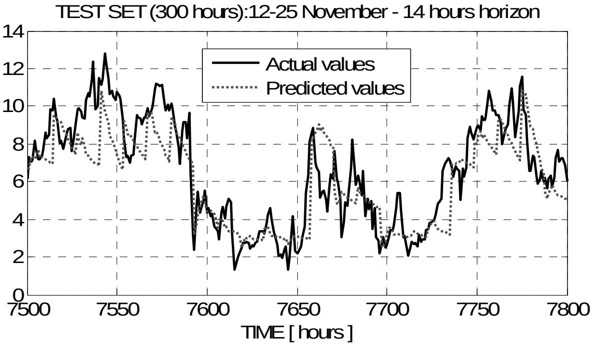

Fig. 3: Wind speed forecasting – sample results

3. WIND/CAES

The schematic of the hybrid power plant considered is presented in Fig. 4.

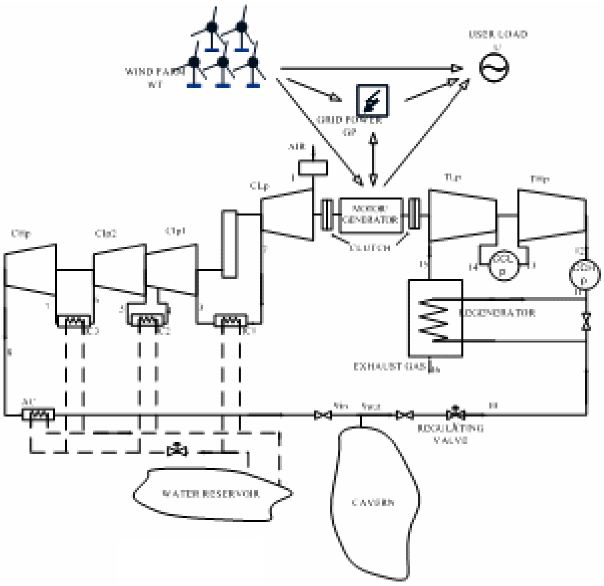

Fig. 4: – Power Plant Schematic

The CAES aspect is based on the Alabama Electric Cooperative McIntosh Power Plant, described in several publications [3][4][5].

The hybrid power plant consists of these basic components:

- Wind Turbines (WT) with electric generator;
- Compressor train (four-stage compressors CLp, CIp1, CIp2 and CHp, inter-coolers IC1, IC2 and IC3 and after-cooler AC);
- Motor/Generator M/G;
- Clutch F;
- Compressed Air Storage (cavern) ;
- Regulating Valve V, to control the air flow from the cavern.
- Turbine expander train (including two-stage expanders THp and TLp and combustors CCHp-CCLp) with regenerator R.
- Connection to grid power GP, for managing integrations and/or surplus.
- Electric User U.

Different operation modes can be considered in this plant. Energy from the wind turbines (WT) can be provided to the motor (M), to the grid power (GP) or directly to the user. Grid power (GP) can be supplied to the user, while the electricity generated from CAES can be economically provided only to the user.

Basic hypotheses include:

- Wind-generated power is used primarily to satisfy the load.
- Surplus power either can be delivered to the compressors or sold to the grid.
- The power required by a load, above that provided by wind turbines, can be provided by CAES and/or by the grid.

In the following sections a brief overview on the adopted models is provided. Refer to [8] for a more detailed description.

Wind Turbines

The wind turbine adopted in this study is the *GE 1.5sle*. The main technical specifications are summarized in Table 2.

Table 2: 1.5sle Technical specifications [12]

Rated capacity [MW]	1.5
Cut-in wind speed [m/s]	3.5
Cut-out wind speed [m/s]	25
Rated wind speed [m/s]	12
Number of rotor blades	3
Rotor diameter [m]	77
Swept area [m^2]	4657

Compressors

A three-body compressor train has been considered with three intercoolers and an after-cooler [5].

Variable incoming wind power and very low off-peak power rates preclude using only wind power for driving the compressors. Accordingly, to maintain operating conditions close to the design conditions, the compressors (total consumption ~50 MW [5]) are partly driven by the wind farm and partly (if necessary) by electricity provided by the power grid.

Cavern

A conventional “un-compensated” constant volume cavern has been considered, with a volume of 0.56x10^6 m^3 [5]. Due to the large capacity of the cavern and the relatively short residence time, heat losses are ignored. For the expander train operation, the maximum allowable pressure is 75 bar and the minimum allowable pressure is 48.3 bar [5].

Gas turbines (turbo expanders)

A two-stage expander has been considered (total production ~110 MW [5][13]), with two combustion chambers and a regenerator. The off-design operation required to follow the user electric load, has been estimated by an improved Flügel formula [14].

The assumed combustion temperatures are conservative, 810 K at the inlet to the high-pressure expander and 1145 K at the inlet to the low-pressure expander [5]. Furthermore, constant rotating speed has been assumed.

Fig. 5 shows the ratio between the actual and the design efficiency as a function of electrical energy provided by the gas turbine. At low loads, the ratio falls off and its minimum (10% of maximum power) is about 0.7 of the design value.

Fig. 5: Off-design operation - turbine efficiency

4. WIND POWER AND ELECTRIC LOAD

Wind power production has been estimated using wind speed data for the year 2002 acquired at the Weather Station *ID 226* in Turi (BA), Italy; these data, sampled each 10 minutes, are shown in Fig. 6. Fig. 7 shows a histogram of the acquired data.

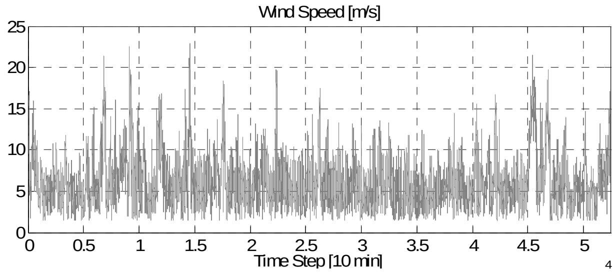

Fig. 6: Wind Speed

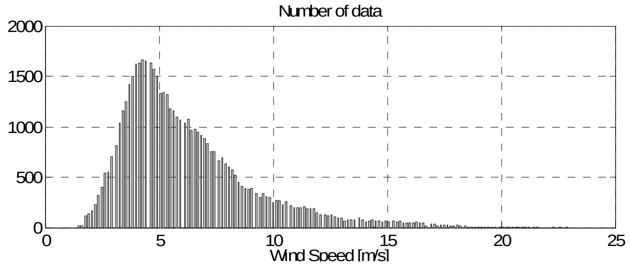

Fig. 7: Wind Speed data distribution

For the assumed electric load, a typical variable load for Italy has been employed. The data (some of which are shown in Fig. 8 and Fig. 9) have the same distribution and characteristics of the Italian national consumption, including a maximum value of around 125 MW [15].

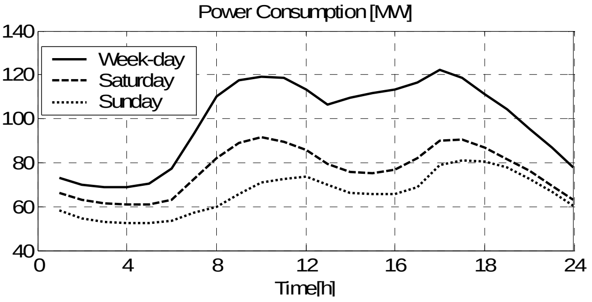

Fig. 8: Typical winter electric load (January)

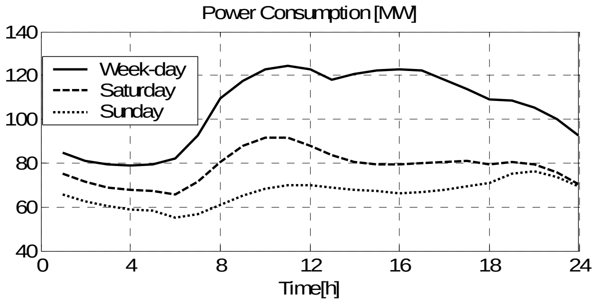

Fig. 9: Typical summer electric load (July)

5. PLANT PERFORMANCE

5. 1 Energetic analysis

To analyze the plant energetic performance, a global efficiency has been introduced to compare the alternative solutions. A global efficiency has been defined as:

$$\eta = \frac{E_{out}}{E_C + m_f H_i} \qquad (5)$$

For an environmental impact analysis, CO_2 emissions have been estimated, considering the emissions produced by the plant and those corresponding to the purchased grid power. In both cases, it is assumed that CO_2 is produced by burning methane. This simplifying assumption does not take into account that grid power is produced by a mix of power plants, with different environmental impact.

5. 2 Economic analysis

Investment Cost Estimation

Owing to economies of scale in production, the capital cost for wind turbines, in €/kW, decreases as the number of wind turbines increases, as shown in Fig. 10.

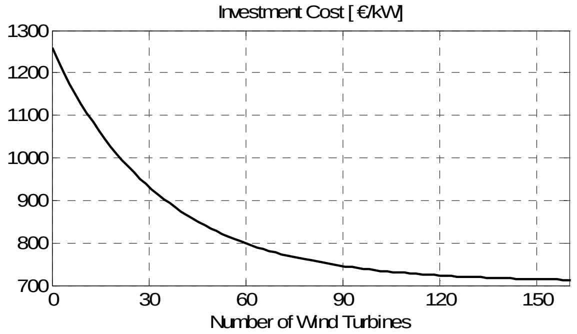

Fig. 10: Investment Cost vs. Wind Farm size [16]

The capital costs of CAES can be simply obtained by considering power-specific and storage-specific contributions. The former is the cost to generate electricity with a storage technology, and the latter is the cost to develop a storage reservoir. Their values are 130 €/kW and 120 €/kW, respectively [17].

In addition, the cost to develop an underground reservoir storage (storage-specific cost) has to be estimated: for a solution-mined salt cavern an investment cost of 0.75 €/kWhe has been assumed [17].

The balance of plant includes other subsystems required for operation of the plant (electrical, mechanical, hydraulic and miscellaneous systems); this cost is estimated as 130 €/kW [17].

Long-distance electricity transmission will be a critical component in the development of large-scale wind farms. Its cost depends on transmission capacity and on distance between power plant and grid/user. The cost has been estimated as 345 €/kW (for a transmission distance of 1000 km) [17].

Operational and Maintenance Costs

The economic model evaluates the annual maintenance and operational costs due to the electrical energy and the methane purchased from the respective providers, according to the Italian energy market [18]; the model also considers the possible revenues due to the sale of surplus electricity. Recent changes in the Italian national consumption has leaded to new electricity prices and time-step definition, [18].

The economic feasibility of the investment is evaluated by means of Simple Pay-Back (SPB), Net Present Value (NPV) and Profitability Index (PI), defined as the ratio between present value of annual savings and investment costs. In this model a time horizon of 10 years and a capital charge rate of 10% have been assumed.

5. RESULTS

In a previous work [8], a parametric analysis has been carried out in order to evaluate power plant performance as function of installed wind power. The analysis considered wind farm sizes from 0 to 150 turbines (0 to 225 MW of installed power), with and without the CAES plant. A similar analysis has been carried out using the latest updated energy prices and the proposed management based on wind speed forecasting. Sample results are shown in Table 3 and Table 4.

Table 3: HPP Performance indexes

# Turbines	*Investment [M€]*	*Savings [M€]*	*SPB [years]*	*NPV [M€]*	*Global Eff. [%]*	*PI [/]*	*Spec CO_2 [kg/MWh]*
0	52.9	9.63	5.5	21.0	46.55	1.36	437.6
20	85.2	18.16	4.7	55.3	46.41	1.65	394.4
50	120.9	30.14	4.0	112.3	46.09	1.93	332.3
80	153.3	41.05	3.7	164.1	45.84	2.07	272.4
110	186.3	51.58	3.6	212.6	45.60	2.14	222.0
140	220.9	61.43	3.6	253.5	45.40	2.15	180.9

Table 4: Economic analysis of HPP solution with and without wind speed forecasting

# Turbines	*Investment [M€]*	*Savings* **without forecasting** *[M€]*	*Savings* **with forecasting** *[M€]*	*Δ savings [%]*	*PI [/]* **without forecasting** *[M€]*	*PI [/]***with forecasting** *[M€]*
0	52.92	8.15	9.63	18.18	1.14	1.36
20	85.23	16.47	18.16	10.25	1.50	1.65
50	120.86	27.92	30.14	7.96	1.79	1.93
80	153.27	39.14	41.05	6.16	1.98	2.07
110	186.25	49.56	51.58	4.09	2.06	2.14
140	220.89	59.57	61.43	3.13	2.08	2.15

The *savings* reported in the results are calculated by comparing the operational cost for the case where the load is satisfied only by grid power (93.2 M€) to the operational and maintenance cost for the proposed plant.

In Table 4 and Fig. 11 the economic benefits of the proposed HPP with and without wind speed forecasting are compared.

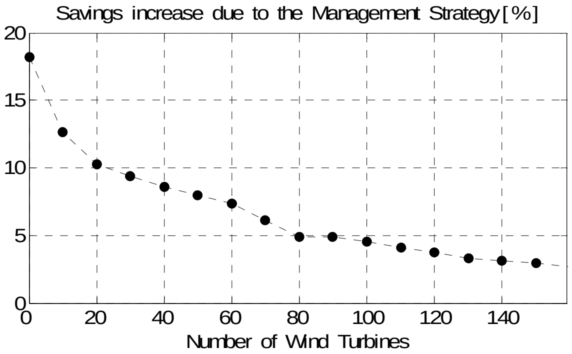

Fig. 11: Economic benefits achievable with wind speed forecasting

As shown in Fig. 11, the proposed management strategy increases annual savings, but with an advantage that decreases with wind farm size. This result can be easily explained by noticing that the larger the size of the wind farm, the less energy is required by gas turbines. For a high number of wind turbines (lower net load), CAES can generate even for 12-14 hours a day, thus avoiding the possible management problems described above (*section 2.1*).

For a complete analysis performance indexes of the proposed HPP (with wind speed prediction) are compared to indexes related to a wind farm/grid solution (Table 5, Fig. 12 Fig. 13).

Table 5: Wind farm performance indexes

# Turbines	*Investment [M€]*	*Savings [M€]*	*SPB [years]*	*NPV [M€]*	*PI [/]*	*Spec CO_2 [kg/MWh]*
20	32.3	9.08	3.6	37.7	2.17	467.2
50	68.0	22.60	3.0	106.6	2.57	381.0
80	100.4	35.31	2.8	172.3	2.72	303.1
110	133.3	46.71	2.9	227.4	2.71	241.0
140	167.2	57.42	2.9	276.2	2.65	192.8

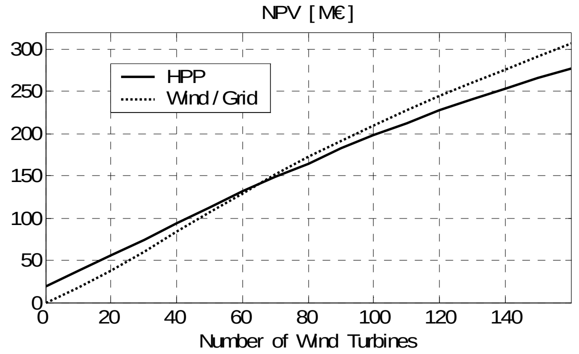

Fig. 12: Net Present Value comparison between a HPP solution and wind farm/grid solution

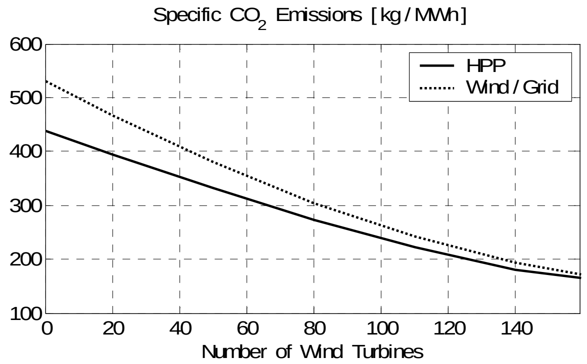

Fig. 13: Specific CO_2 emissions comparison between a HPP solution and wind farm/grid solution

In Fig. 12 the Net Present Value for both HPP and simple wind farm cases is shown; all solutions have a positive and satisfactory NPV, increasing with the number of wind turbines. From an economic point of view, the HPP solution is preferred only when there are fewer than 70 wind turbines (105 MW installed power).

As shown in Table 3 and Table 5, instead, the optimal number (maximizing the PI) of wind turbines in the case of HPP is about 140, while it is about 80 in the case of a wind farm/grid solution. The most effective use of the invested capital is achieved with these values for the respective types of plant.

The proposed HPP reduces specific CO_2 emissions but with an advantage that decreases with wind farm size (Fig. 13): the larger the size of the wind farm, the more the CAES plant works in off-design conditions at lower efficiency (thus producing more specific CO_2 emissions).

Further economic benefits are achievable by the HPP due to the new energy prices, with respect to the previous prices definition [8][18]. Fig. 14 compares savings for both cases (without applying the described management strategy).

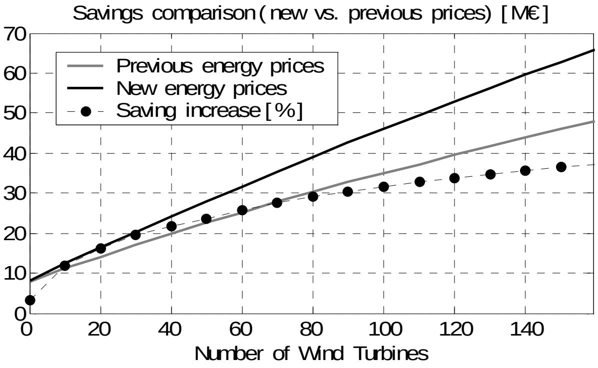

Fig. 14: New energy prices – further benefits.

The presented results evidence also that the design of plant components is not trivial and strictly connected to the actual energy market, to management strategy, to the time distribution of incoming energy and electric load.

CONCLUSIONS

A thermo-economic model of a CAES/Wind power plant, coupled with ANN-based wind speed forecasting model has been presented.

Besides the expected benefits in terms of operational costs and CO_2 emissions due to the proposed HPP [8], the results show further economic advantages achievable with proper system management based on predicted wind speed data.

Without the management strategy, with respect to the case where the load is satisfied only by grid power, operational costs are reduced by 9% (no wind turbines) to 64% (140 wind turbines), while CO_2 emissions are reduced by 41% (no wind turbines) to 76% (140 wind turbines). With respect to the wind farm/grid solution, operational costs are reduced by 9% (20 wind turbines) to 6% (140 wind turbines), while CO_2 emissions are reduced by 16% (20 wind turbines) to 7% (140 wind turbines).

Using system management based on predicted wind speed data, annual savings for the proposed HPP increase by 18% (no wind turbines) to 3% (140 wind turbines) leading to a further reduction of operational costs by 2 – 5 % for the analyzed scenarios.

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